LBNF/DUNE and the Hunt for Leptonic CP Violation

FPCP 2016, 6-9 June 2016, Caltech

Mary Bishai
for the DUNE Collaboration

June 1, 2016

Outline

Oscillations in the 3-flavor ν SM

In the ν 3-flavor model matter/anti-matter asymmetries in neutrinos are best probed using $\nu_\mu/\bar{\nu}_\mu \to \nu_e/\bar{\nu}_e$ oscillations (or vice versa). With terms up to second order in $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$ and $\sin^2\theta_{13}$, (M. Freund. Phys. Rev. D 64, 053003):

$$P(\nu_\mu \to \nu_e) \cong P(\nu_e \to \nu_\mu) \cong \underbrace{P_0}_{\theta_{13}} + \underbrace{P_{\sin\delta}}_{\text{CP violating}} + P_{\cos\delta} + \underbrace{P_3}_{\text{solar oscillation}}$$

where **for oscillations in vacuum:**

$$P_0 = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(\Delta),$$

$$P_3 = \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2(\Delta),$$

$$P_{\sin\delta} = \alpha\, 8J_{cp}\sin^3(\Delta),$$

$$P_{\cos\delta} = \alpha\, 8J_{cp}\cot\delta_{CP}\cos\Delta\sin^2(\Delta),$$

and where

$$\Delta = \Delta m^2_{31} L/4E$$

Oscillations in the 3-flavor ν SM

LBNF/DUNE and the Hunt for Leptonic CP Violation

Mary Bishai for the DUNE Collaboration

In the ν 3-flavor model matter/anti-matter asymmetries in neutrinos are best probed using $\nu_\mu/\bar{\nu}_\mu \rightarrow \nu_e/\bar{\nu}_e$ oscillations (or vice versa). With terms up to second order in $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$ and $\sin^2\theta_{13}$, (M. Freund. Phys. Rev. D 64, 053003):

$$P(\nu_\mu \rightarrow \nu_e) \cong P(\nu_e \rightarrow \nu_\mu) \cong \underbrace{P_0}_{\theta_{13}} + \underbrace{P_{\sin\delta}}_{\text{CP violating}} + P_{\cos\delta} + \underbrace{P_3}_{\text{solar oscillation}}$$

where **for oscillations in matter with constant density:**

$$P_0 = \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(A-1)^2}\sin^2[(A-1)\Delta],$$

$$P_3 = \alpha^2\cos^2\theta_{23}\frac{\sin^2 2\theta_{12}}{A^2}\sin^2(A\Delta),$$

$$P_{\sin\delta} = \alpha\frac{8J_{cp}}{A(1-A)}\sin\Delta\sin(A\Delta)\sin[(1-A)\Delta],$$

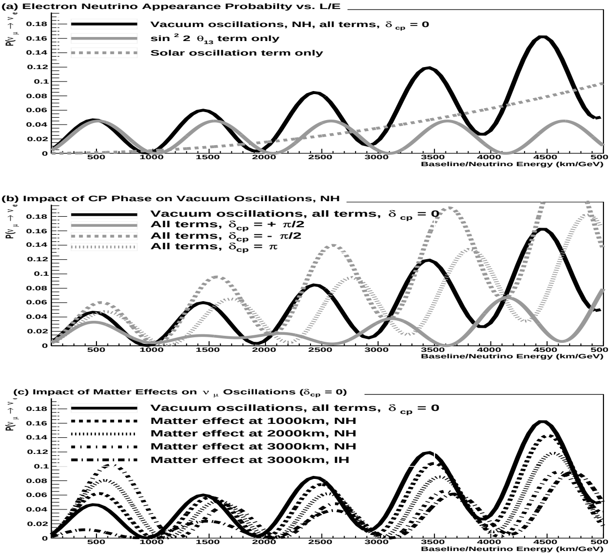
$$P_{\cos\delta} = \alpha\frac{8J_{cp}\cot\delta_{CP}}{A(1-A)}\cos\Delta\sin(A\Delta)\sin[(1-A)\Delta],$$

and where

$$\Delta = \Delta m^2_{31}L/4E \text{ and } A = \sqrt{3}G_F N_e 2E/\Delta m^2_{31}.$$

For $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, $P_{\sin\delta} \rightarrow -P_{\sin\delta}$

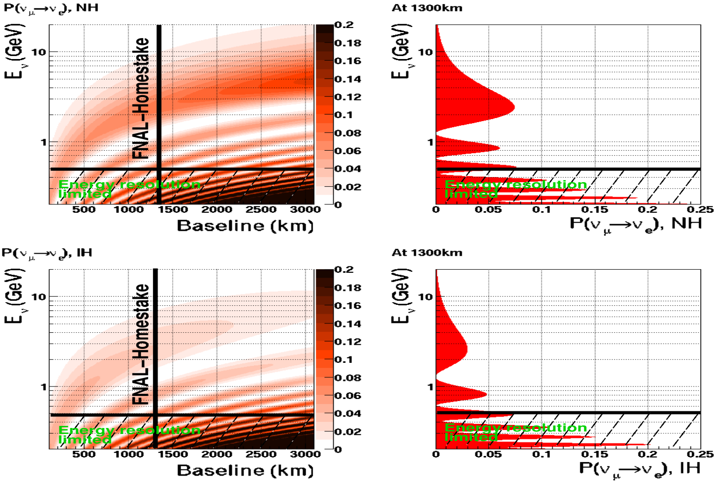
3 Flavor Oscillations with CPV and Matter Effects



$P(\nu_\mu \rightarrow \nu_e)$ vs L and E ($\delta_{cp} = 0$)

The $\nu_\mu \rightarrow \nu_e$ oscillation probability maxima occur at

$$\frac{L\ (\mathrm{km})}{E_n(\mathrm{GeV})} = \left(\frac{\pi}{2}\right)\frac{(2n-1)}{1.27 \times \Delta m^2_{31}(\mathrm{eV}^2)} \approx (2n-1) \times \frac{515\ \mathrm{km}}{\mathrm{GeV}}$$



CP Violation in ν SM

The charge-parity (CP) asymmetry is defined as

$$\mathcal{A}_{cp} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

$$\mathcal{A}_{cp} \sim \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right) + \text{matter effects}$$

W. Marciano, Z. Parsa, Nucl.Phys.Proc.Suppl. 221 (2011)

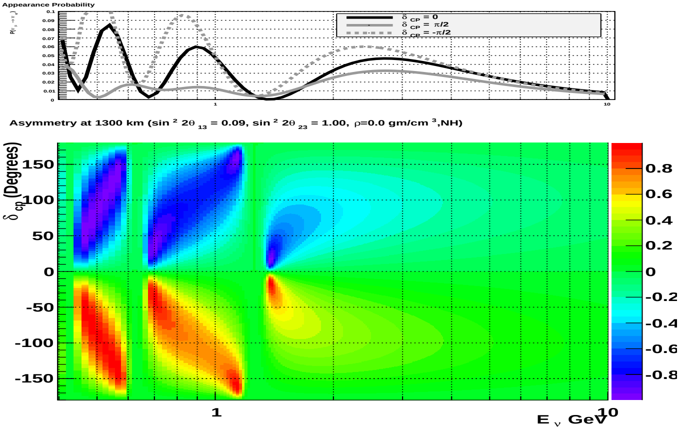
The CP phase δ_{cp} is unknown. CP is violated when $\delta_{cp} \neq 0, \pi$

The 4 most important things to know about ν CPV

- $\mathcal{A}_{cp} \propto 1/\sin\theta_{13} \Rightarrow$ Large θ_{13} makes CPV searches HARDER.
- $\mathcal{A}_{cp} \propto 1/\tan\theta_{23} \Rightarrow$ Large $\sin(\theta_{23})$ = smaller CPV (octant!)
- $\mathcal{A}_{cp} \propto 1/E_\nu \Rightarrow$ CP asymmetries are larger at lower energies
- $\mathcal{A}_{cp} \propto L \Rightarrow$ **CP asymmetries are larger at longer baselines**

CP Asymmetry vs E_ν and δ_{cp}

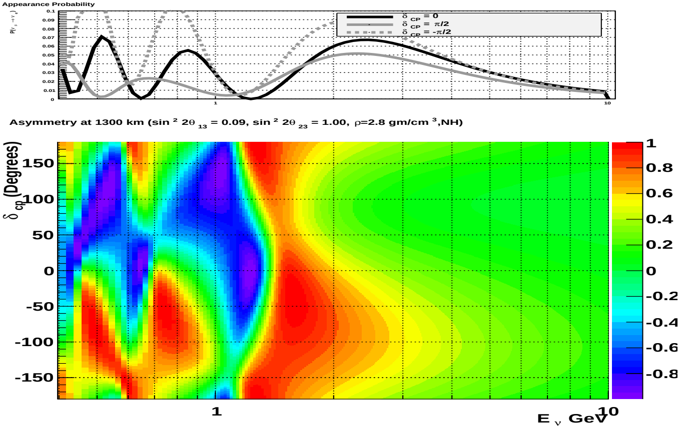
NH, Vacuum, 1300km



Asymmetries are larger near minima
BUT, events appear at the maxima!

CP Asymmetry vs E_ν and δ_{cp}

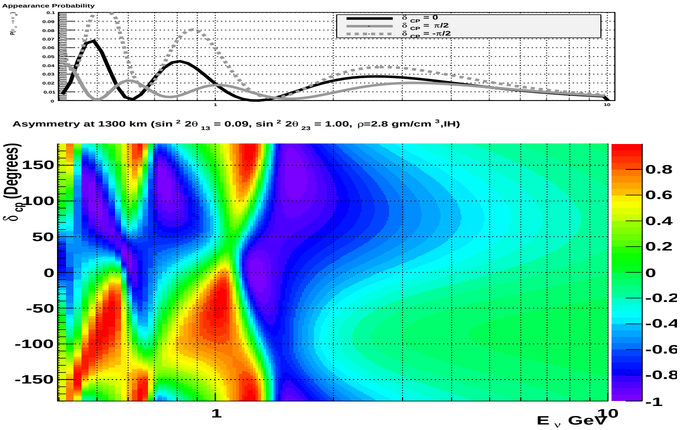
NH, $\rho = 2.8gm/cm^3$, 1300km



Asymmetries are larger near minima
BUT, events appear at the maxima!

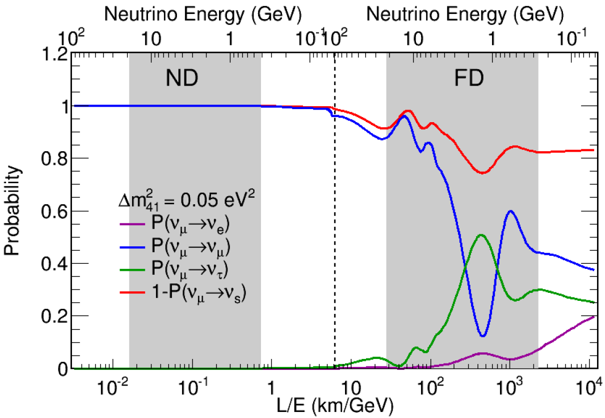
CP Asymmetry vs E_ν and δ_{cp}

IH, $\rho = 2.8gm/cm^3$, 1300km

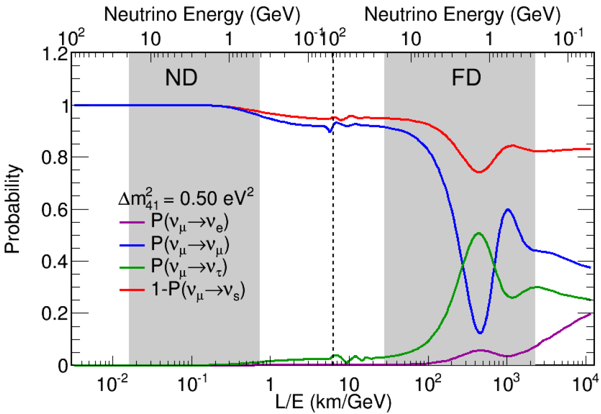


Asymmetries are larger near minima
BUT, events appear at the maxima!

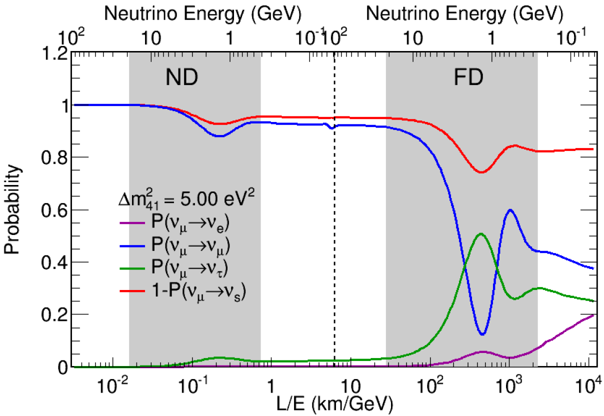
Impact of Sterile Neutrinos on ν Oscillations



Impact of Sterile Neutrinos on ν Oscillations

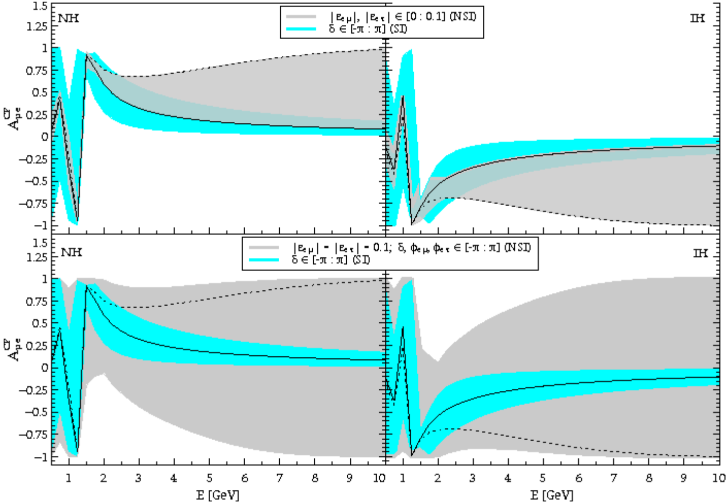


Impact of Sterile Neutrinos on ν Oscillations



NSI and CPV

NSI could also impact CPV interpretation in long-baseline (M. Masud, A. Chatterjee, P. Mehta arXiv:1510.08261):



Results from Current $\nu_\mu \rightarrow \nu_e$ Long-Baseline Experiments and Near Future

$\nu_\mu \rightarrow \nu_e$ Event Rates - Various Experiments.

arXiv:1307.7335, for 50 kton.years* of exposure. No detector effects

Experiment	Baseline	Super Beams $\nu_\mu \rightarrow \nu_\mu$	$\nu_\mu \rightarrow \nu_\tau$	$\nu_\mu \rightarrow \nu_e$
T2K 30 GeV, 750 kW 9×10^{20} POT/year	295km (off-axis)	900	< 1	40 - 70
MINOS LE 120 GeV, 700 kW 6×10^{20} POT/year	735km	11,000	115	230-340
NOνA 120 GeV, 700 kW 6×10^{20} POT/year	810km (off-axis)	1500	10	120 - 200
DUNE LE† 80 GeV, 1.2MW 1.5×10^{21} POT/year	1,300km	4300	160	350 - 600
DUNE ME† 80 GeV, 1.2MW 1.5×10^{21} POT/year	1,300km	12,000	690	290 - 430

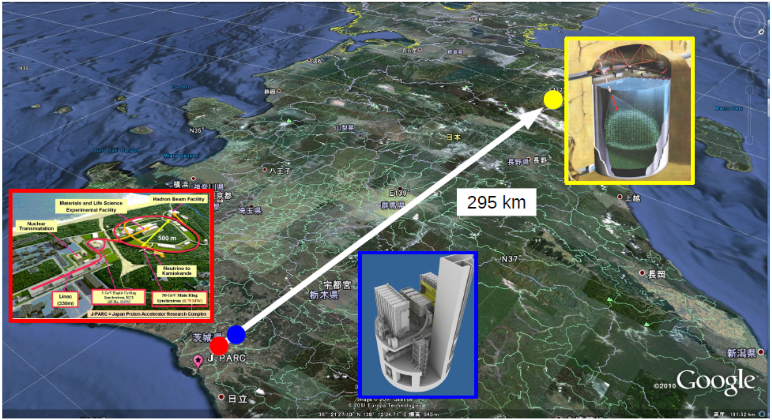
* Facility duty factor taken into consideration

† 2014 CDR Reference Design with NuMI style focusing

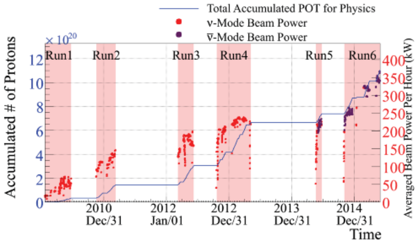
Even with maximal CP, event rate is a ≤ 10 $\nu_\mu \rightarrow \nu_e$ per kT.MW.yr

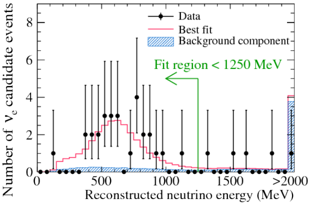
Experimental challenge for CPV measurements: STATISTICS!

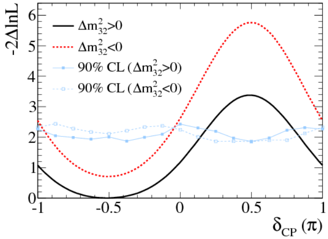
The T2K Experiment (295km baseline)



T2K Results





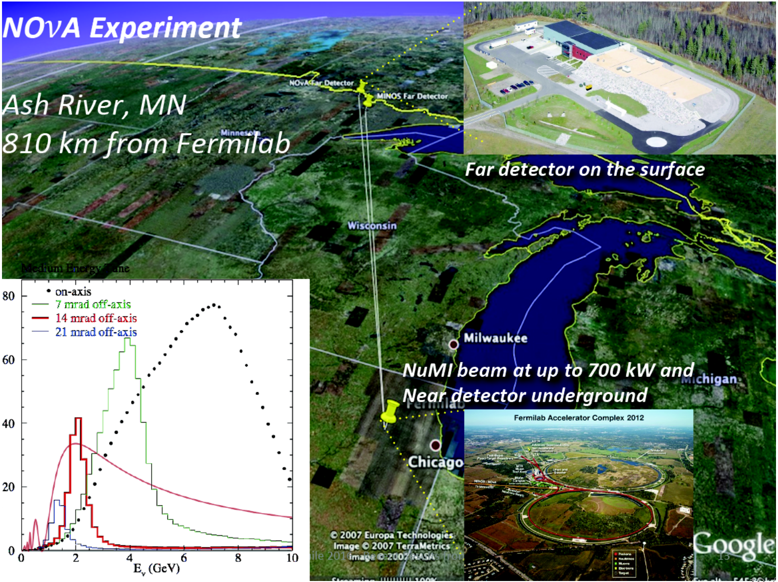


With 6.57×10^{20} POT in ν mode Observe 28 ν_e with 4.9 ± 0.6 background

With 4.04×10^{20} POT in $\bar{\nu}$ mode Observe 3 ν_e candidates. Expect 1.51 to 1.77 background.

Favors maximal CP at NH

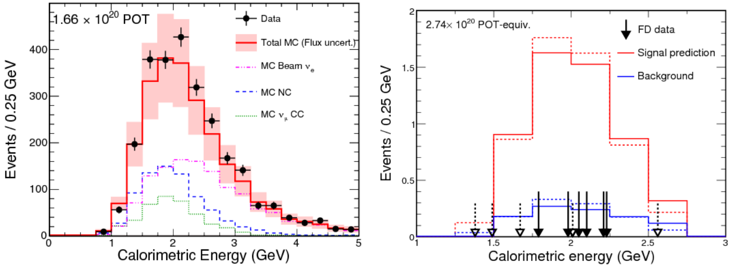
The NOνA Experiment (810km Baseline)



First Results from NOνA

arXiv:1601.05022

With 2.74×10^{20} protons-on-target:

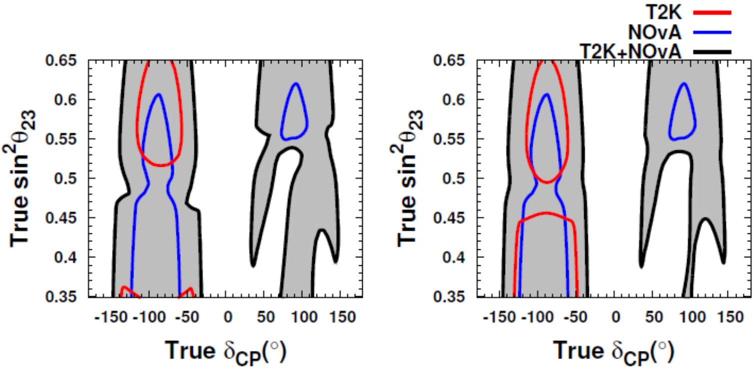


6 LID candidates
(3.3 σ signal of ν_e appearance)
11 LEM candidates
(5.5 σ signal of ν_e appearance)

LID analysis disfavors $0.1\pi < \delta_{CP} < 0.5\pi$ in the IH at 90% C.L.

T2K+NOνA Prospects

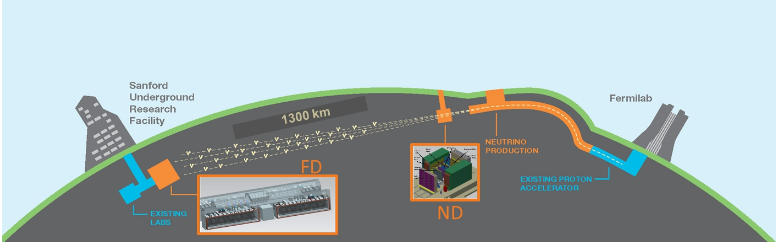
T2K (7.8×10^{21} pot) and NOνA (1.8×10^{21} pot) combined, exclusion of $\delta_{cp} = 0$ at 90% C.L. (K. Abe et. al. arXiv:1409.7469):



(a) 1:0 T2K, 1:1 NOνA ν:$\bar{\nu}$, NH

(b) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, NH

Future Experimental Landscape: LBNF/DUNE

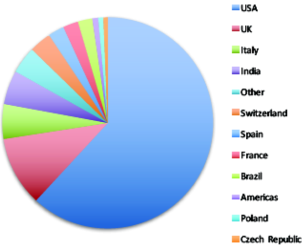


- **Long baseline experiment with a wide-band beam and a 1300km baseline from Fermilab to the Sanford Underground Research Facility in Lead, SD.**
- **Highly capable mult-purpose Near Detector at Fermilab**
- **40 kton fiducial (80 kton total) Liquid Argon Time Projection Chambers (LArTPC) at SURF. Both single and dual-phase LArTPC options under consideration.**

The DUNE Collaboration

Formed in Jan 2015 from combination of the US-based LBNE and LBNO experiments.

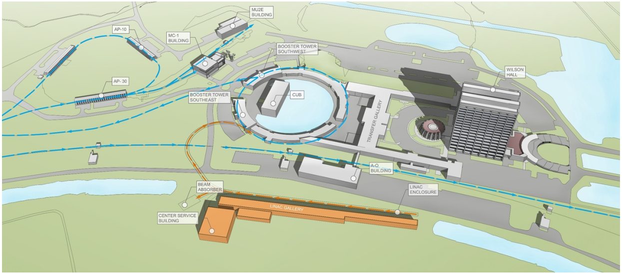
856 Collaborators **from 149 Institutions in 29 Nations**



Armenia, Belgium, Brazil, Bulgaria, Canada, Colombia, Czech Republic, Finland, France, Greece, India, Iran, Italy, Japan, Madagascar, Mexico, Netherlands, Peru, Poland, Romania, Russia, Spain, Sweden, Switzerland, Turkey, UK, USA, Ukraine

Fermilab Accelerator upgrades for DUNE

Planned upgrades to the Fermilab complex to increase proton intensity:



PIP-II replaces upstream portion of linac feeding into 8 GeV Booster:
1.03 MW at 60 GeV
1.07 MW at 80 GeV
1.20 MW at 120 GeV

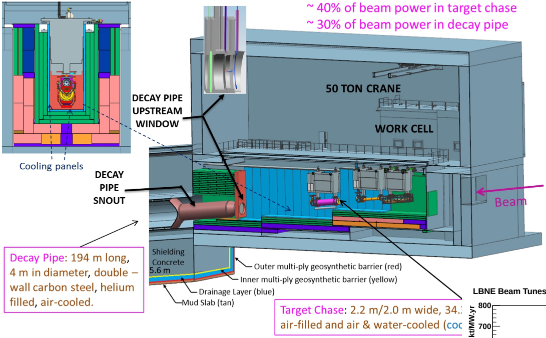
Ready by 2025

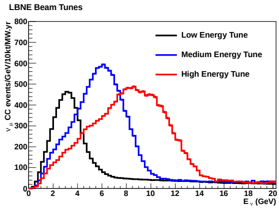
Further upgrades (PIP-III) would replace booster with Rapid Cycling Synchrotron (RCS) or SC Linac. Currently in R&D stage.

$\geq$ 2.0 MW at 60 GeV
$\geq$ 2.3 MW at 120 GeV

The LBNF Beamline for DUNE

Advanced conceptual design *tunable wide-band* NuMI-style focusing:

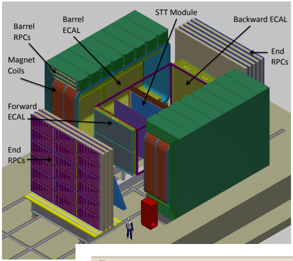




Optimized focusing design with 3 horns $\sim$ 30% more flux for CPV

The DUNE Near Detector Reference Design

Reference design is the Fine Grained Tracker based on the "LBNE-India Detailed Project Report (DPR)" submitted to DAE, India in 2012. **Alternative/additional designs under consideration by DUNE**



Performance Metric	Value
Vertex resolution	0.1 mm
Angular resolution	2 mrad
E_e resolution	5%
E_μ resolution	5%
$\nu_\mu/\overline{\nu}_\mu$ ID	Yes
$\nu_e/\overline{\nu}_e$ ID	Yes
NCπ^0/CCe rejection	0.1%
NCγ/CCe rejection	0.2%
NCμ/CCe rejection	0.01%

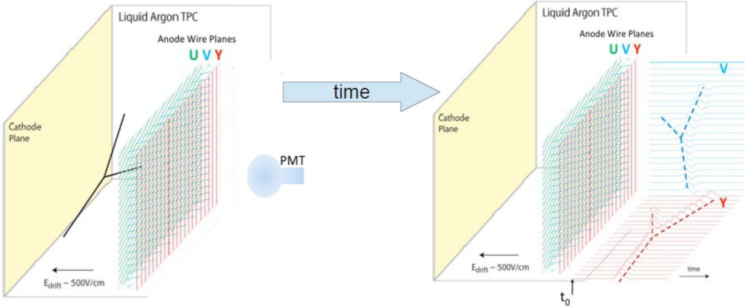
Parameter	Value
STT detector volume	$3 \times 3 \times 7.04$ m^3
STT detector mass	8 tons
Number of straws in STT	123,904
Inner magnetic volume	$4.5 \times 4.5 \times 8.0$ m^3
Targets	1.27-cm thick argon ($\sim$ 50 kg), water and others
Transition radiation radiators	2.5 cm thick
ECAL X_0	10 barrel, 10 backward, 18 forward
Number of scintillator bars in ECAL	32,320
Dipole magnet	2.4-MW power; 60-cm steel thickness
Magnetic field and uniformity	0.4 T; < 2% variation over inner volume
MuID configuration	32 RPC planes interspersed between 20-cm thick layers of steel

Measuring the ν Flux with the DUNE ND

Technique	Flavor	Absolute normalization	Relative flux $\Phi(E_\nu)$	Near Detector requirements
NC Scattering $\nu_\mu e^- \to \nu_\mu e^-$	ν_μ	2.5%	$\sim 5\%$	e ID θ_e Resolution e^-/e^+ Separation
Inverse muon decay $\nu_\mu e^- \to \mu^- \nu_e$	ν_μ	3%		μ ID θ_μ Resolution 2-Track (μ+X) Resolution μ energy scale
CC QE $\nu_\mu n \to \mu^- p$ $Q^2 \to 0$	ν_μ	$3-5\%$	$5-10\%$	D target p Angular resolution p energy resolution Back-Subtraction
CC QE $\overline{\nu}_\mu p \to \mu^+ n$ $Q^2 \to 0$	$\overline{\nu}_\mu$	5%	10%	H target Back-Subtraction
Low-ν_0	ν_μ		2.0%	μ^- vs μ^+ E_μ-Scale Low-E_{Had} Resolution
Low-ν_0	$\overline{\nu}_\mu$		2.0%	μ^- vs μ^+ E_μ-Scale Low-E_{Had} Resolution
Low-ν_0	$\nu_e/\overline{\nu}_e$	1-3%	2.0%	e^-/e^+ Separation (K^0_L)
CC	ν_e/ν_μ	<1%	~2%	e^- ID & μ^- ID p_e/p_μ Resolution
CC	$\overline{\nu}_e/\overline{\nu}_\mu$	<1%	~2%	e^+ ID & μ^+ ID p_e/p_μ Resolution
Low-ν_0/CohPi	$\overline{\nu}_\mu/\nu_\mu$	~2%	~2%	μ^+ ID & μ^- ID p_μ Resolution E_{Had} Resolution

Near to Far Extrapolation

Liquid Argon TPCs: Single Phase



The DUNE Far Detector LArTPC

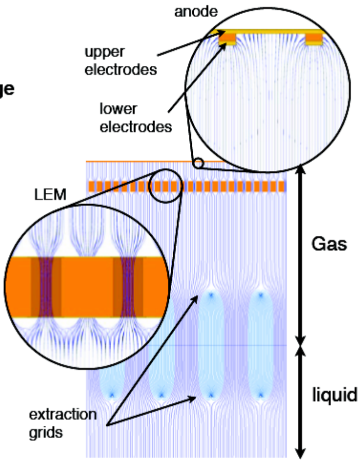
Liquid Argon TPCs: Dual Phase

4.) Charge collection on a 2D anode readout (symmetric unipolar signals with two orthogonal views)

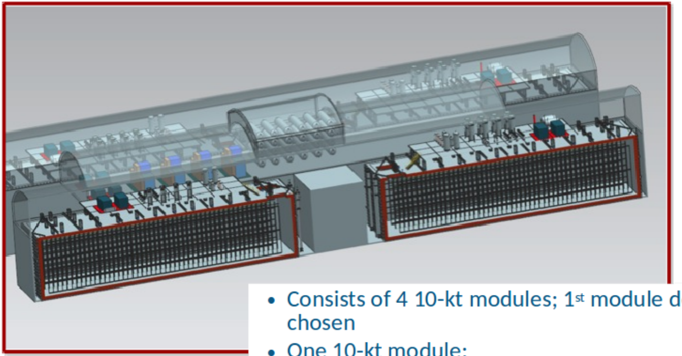
3.) Charge multiplication in the holes of the Large Electron Multiplier (LEM)

2.) Drift electrons are efficiently emitted into the gas phase

1.) Ionization electrons drift towards the liquid argon surface



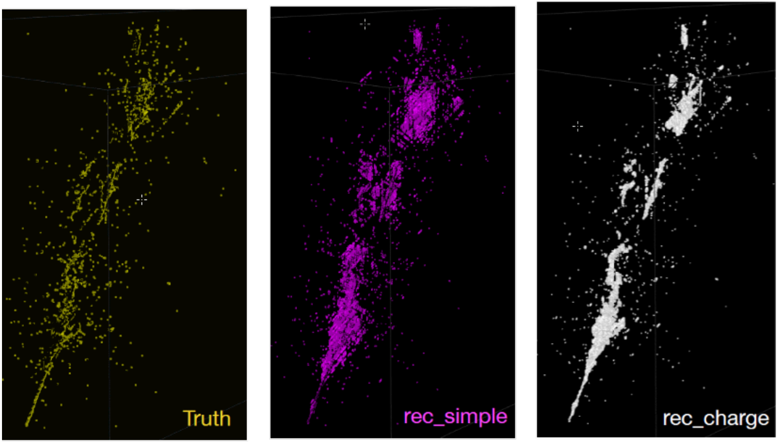
The DUNE Far Detector LArTPC



- Consists of 4 10-kt modules; 1st module design chosen
- One 10-kt module:
  - Active volume 12m x 14.5m x 58m
  - 150 total APAs; 384,000 sense wires
- Each APA: 2.3m x 6m; 2560 sense wires
- 3 sense wire planes; wire pitch: ~5 mm
- Drift field: 500 V/cm
- Maximum drift distance: 3.6 m (~2 ms)

Simulation/Reconstruction in a Single Phase LArTPC (`http://www.phy.bnl.gov/wire-cell`)

Example: a 1.5 GeV electron

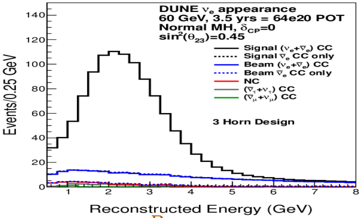


Use only geometry information

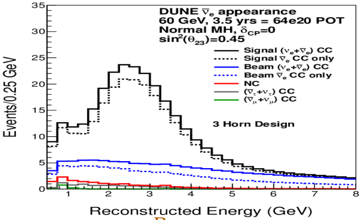
Use geometry and charge information

DUNE Event Spectra

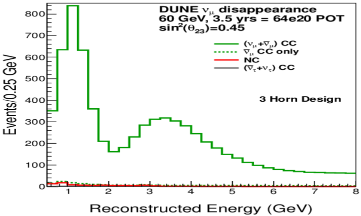
Exposure: 150 kT.MW.yr (equal $\nu/\bar{\nu}$) 1MW.yr = 1×10^{21} p.o.t at 120 GeV. ($\sin^2 2\theta_{13} = 0.085$, $\sin^2 \theta_{23} = 0.45$, $\delta m^2_{31} = 2.46 \times 10^{-3}$ eV^2)



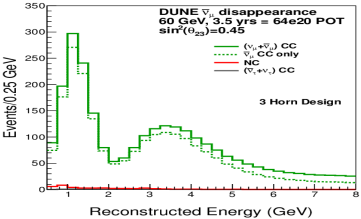
930 ν_e, 5 $\bar{\nu}_e$, 204 ν_e^{Beam}, 17 NC, 19 ν_τ, 3 ν_μ



32 ν_e, 154 $\bar{\nu}_e$, 98 ν_e^{Beam}, 7 NC, 8 ν_τ, 1 ν_μ



7929 ν_μ, 511 $\bar{\nu}_\mu$, 105 bkg

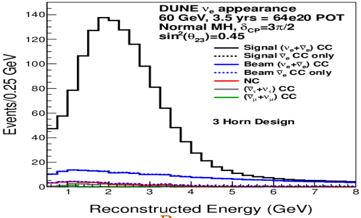


2639 $\bar{\nu}_\mu$, 1424 ν_μ, 59 bkg

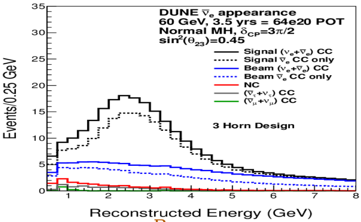
Simultaneous fit to all four samples to determine osc. params

DUNE Event Spectra

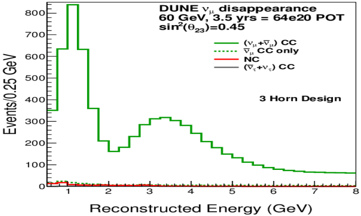
Exposure: 150 kT.MW.yr (equal $\nu/\bar{\nu}$) 1MW.yr $= 1 \times 10^{21}$ p.o.t at 120 GeV. ($\sin^2 2\theta_{13} = 0.085,\ \sin^2\theta_{23} = 0.45,\ \delta m^2_{31} = 2.46 \times 10^{-3}\ \mathrm{eV}^2$)



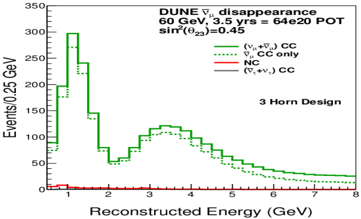
1171 ν_e, 3 $\bar{\nu}_e$, 204 ν_e^{Beam}, 17 NC, 19 ν_τ, 3 ν_μ



39 ν_e, 94 $\bar{\nu}_e$, 98 ν_e^{Beam}, 7 NC, 8 ν_τ, 1 ν_μ



7929 ν_μ, 511 $\bar{\nu}_\mu$, 105 bkg



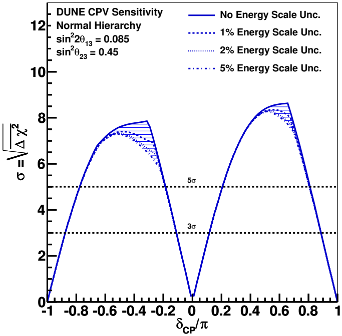
2639 $\bar{\nu}_\mu$, 1424 ν_μ, 59 bkg

Simultaneous fit to all four samples to determine osc. params

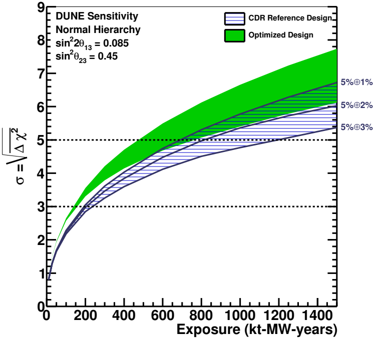
DUNE CP Sensitivity

Source of Uncertainty	MINOS ν_e	T2K ν_e	Goal for DUNE ν_e
Beam Flux	0.3%	3.2%	2%
Interaction Model	2.7%	5.3%	~2%
Energy Scale (ν_μ)	3.5%	Included above	Included in 5% ν_μ uncertainty
Energy Scale (ν_e)	2.7%	2.5% includes all FD effects	2%
Fiducial Volume	2.4%	1%	1%
Total Uncertainty	5.7%	6.8%	3.6%
Used in DUNE sensitivity calculations:			$5\% \oplus 2\%$

CP Violation Sensitivity



50% CP Violation Sensitivity

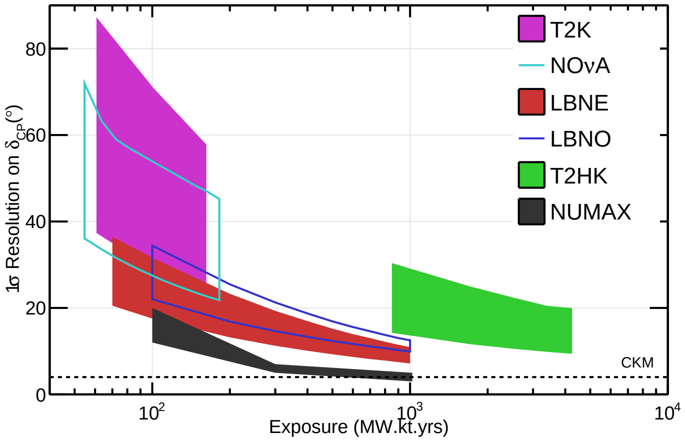


DUNE Physics Milestones (NH)

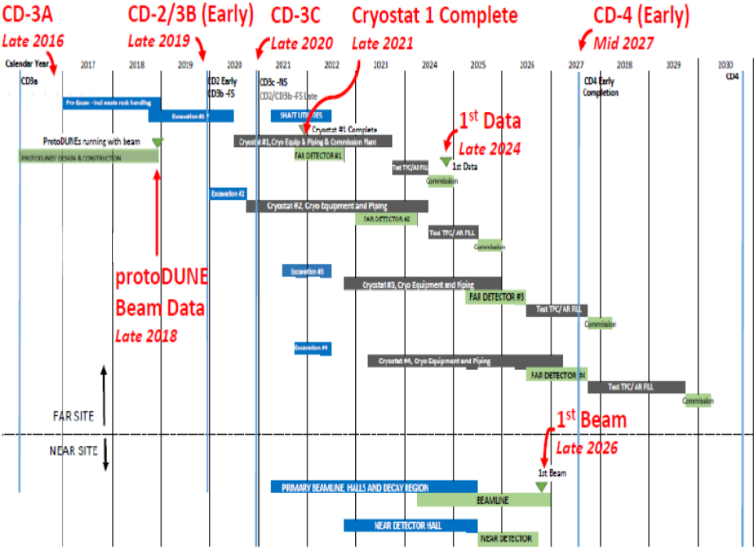
Physics milestone	Exposure kt · MW · year (reference beam)	Exposure kt · MW · year (optimized beam)
1° θ_{23} resolution ($\theta_{23} = 42^\circ$)	70	45
CPV at 3σ ($\delta_{\rm CP} = +\pi/2$)	70	60
CPV at 3σ ($\delta_{\rm CP} = -\pi/2$)	160	100
CPV at 5σ ($\delta_{\rm CP} = +\pi/2$)	280	210
MH at 5σ (worst point)	400	230
10° resolution ($\delta_{\rm CP} = 0$)	450	290
CPV at 5σ ($\delta_{\rm CP} = -\pi/2$)	525	320
CPV at 5σ 50% of $\delta_{\rm CP}$	810	550
Reactor θ_{13} resolution ($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)	1200	850
CPV at 3σ 75% of $\delta_{\rm CP}$	1320	850

Even if CP is maximally violated $\rightarrow$ several years to 5σ discovery

CP Phase Resolution vs Exposure



LBNF/DUNE Schedule



Summary and Conclusions

- **Neutrino CP violation is best measured by studying $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations over long-baselines.**
- **Experiments need to separate CP asymmetries from asymmetries induced by the expected MSW effect as well as new physics effects such as sterile neutrinos (if they exist) and NSI.**
- **The current generation of experiments after a decade of running could rule out $\delta_{\rm CP} = 0$ at 90% C.L. over a large fraction of $\delta_{\rm CP} - \theta_{23}$ space. Combined results from running NOνA and T2K at maximum power could produce evidence for CPV at 3σ** *if it is maximal***.**
- **BUT**
  Only future more capable LB expts can establish CPV in ν and disentangle from other effects.


THANK YOU